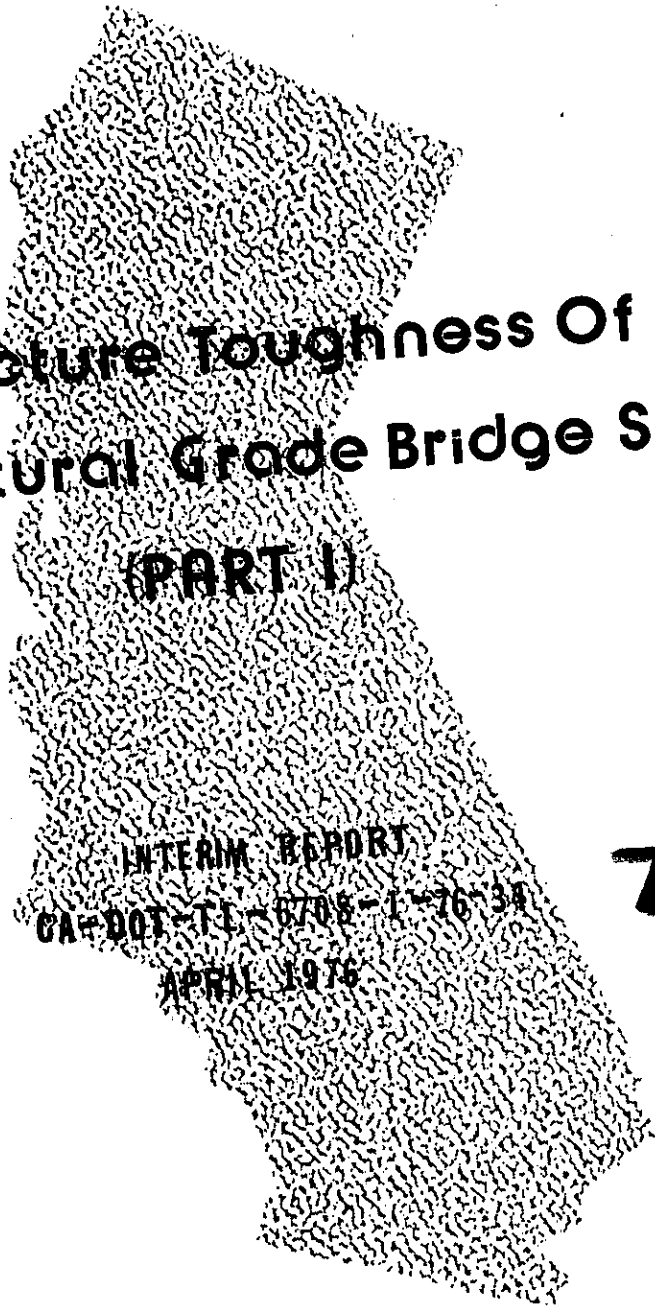
DIVISION OF STRUCTURES AND ENGINEERING SERVICES

TRANSPORTATION LABORATORY

RESEARCH REPORT



Fracture Toughness Of Structural Grade Bridge Steels

(PART I)

INTERIM REPORT

CA-DOT-TL-6708-1-76-34

APRIL 1976

76-34

Prepared in Cooperation with the U.S. Department of Transportation, Federal Highway Administration

Caltrans

CALIFORNIA DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. CA-DOT-TL-6708-1-76-34	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE FRACTURE TOUGHNESS OF STRUCTURAL GRADE BRIDGE STEELS (PART I)		5. REPORT DATE April 1976
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) R. D. Smith, C. B. Kendrick, P. G. Jonas		8. PERFORMING ORGANIZATION REPORT NO. 19603-636708
9. PERFORMING ORGANIZATION NAME AND ADDRESS Office of Transportation Laboratory California Department of Transportation Sacramento, California 95819		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO. D-4-116
12. SPONSORING AGENCY NAME AND ADDRESS California Department of Transportation Sacramento, California 95807		13. TYPE OF REPORT & PERIOD COVERED Interim
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

The brittle fracture resistance or toughness of a bridge steel tends to vary inversely with its grain size at service temperature. The service temperature grain size in turn tends to be proportional to the steel's austenitic grain size at the final rolling or normalizing temperature used to process it. The McQuaid-Ehn test, however, measures the austenitic grain size of a steel specimen at 1700°F, a temperature which may or may not be representative of the final processing temperature of the plate from which the specimen derived.

Since the austenitic grain size varies with the final processing temperature, it follows, that the McQuaid-Ehn grain size doesn't necessarily correlate with fracture toughness. Hence, specifying a fine grain practice, verified by McQuaid-Ehn grain size tests, does not insure that hot rolled steel will be fine grained or suitably resistant to brittle fracture at service temperatures. It only insures that the steel may have these properties if it is control rolled below 1900 F or normalized.

These correlations and the basis for these conclusions are discussed in this report.

17. KEY WORDS Steel, fracture toughness, grain size, fine grain practice, brittle fracture.	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. SECURITY CLASSIF. (OF THIS REPORT) Unclassified	20. SECURITY CLASSIF. (OF THIS PAGE) Unclassified	21. NO. OF PAGES 19	22. PRICE

DH-TL 1242 (Rev. 3-74)

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES & ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

April 1976

FHWA No. D-4-116
TL No. 636708

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this interim research project report titled:

FRACTURE TOUGHNESS OF STRUCTURAL
GRADE BRIDGE STEELS (PART I)

Study made by . . . . Structural Materials Branch

Under the Supervision of . . . . . . Eric F. Nordlin

Principal Investigator . . . . Paul G. Jonas

Co-Investigators . . . . Charles B. Kendrick and
Roger D. Smith

Research Conducted & Reported by . . Roger D. Smith

Assisted by . . . . Steven W. Rutter

Very truly yours,

George A. Hill

GEORGE A. HILL
Chief, Office of Transportation Laboratory

Attachment

CBK:lrb

ACKNOWLEDGEMENTS

The authors of this report wish to express their appreciation for the help and advice provided by their colleagues in the Transportation Laboratory and by representatives from industry.

The contents of this report reflect the views of the Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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INTRODUCTION

In recent years there have been several instances (1,4,5) (one in California) of brittle failures in bridge steel at stresses well below the yield strength. This indicates that brittle fracture is a limiting factor in bridge performance which has not always been properly considered in design.

The resistance of a steel to "brittle" fracture is measured by its plane strain "fracture toughness". This property, represented by the symbol "K_{1c}", is directly proportional to the gross section stress required to start a crack in a specimen that has been sharply notched transverse to that stress. This relation can be represented by the following expression:

$$K_{1c} = C \sigma \sqrt{\pi a} \qquad (1)$$

Where -

"C" is constant function of test specimen shape and notch depth similar to a stress concentration factor,

"σ" is the gross cross section stress applied to the specimen (i.e., stress without considering the cross section area lost to notch depth), and

"a" is the initial notch depth.

This property is measured by subjecting a notched specimen with known "C" and "a" values, to a gradually increasing stress until it cracks at the notch. The stress at which this occurs is entered in expression (1) to get the fracture toughness K_{1c} for the steel in the specimen.

Once the fracture toughness has been determined, expression (1) can be reversed to give:

(2) $$\sigma = \frac{K_{1c}}{C\sqrt{\pi a}}$$

Using expression (2), the stress required to initiate a brittle fracture off a notch of known depth "a" in a structural element of steel of known fracture toughness can be investigated if the values for "C" for a notch in an element of that cross section shape can be derived using the principles of stress analysis.

The standard tests used to directly measure "fracture toughness" are described in ASTM E399. These tests require specimens which are expensive to machine and often too thick to be obtained from "as-rolled" bridge steels. These size and cost shortcomings render the application of direct measurement fracture toughness requirements impractical if not impossible for many bridge steels at this time. This has led to the development of several empirical correlations between "fracture toughness" and Charpy V Notch (CVN) fracture energy in an effort to provide engineering estimates of K_{1c} values from the smaller and less expensive CVN tests and to provide a basis for CVN requirements. At the initiation of this research project (June 8, 1973), however, ASTM A517 was the only bridge steel that had been regularly specified for bridge use with a Charpy impact requirement. This absence, at that time, of established precedents upon which to base CVN requirements caused the Transportation Laboratory to utilize the general relations between grain structure and toughness in attempts to assure at least some degree of resistance to brittle fracture in the other commonly used bridge steels.

Fracture toughness is known to be dependent on the metallurgical properties, namely the grain characteristics (size and type), of the finished steel. Generally, the finer (smaller) the ferrite grain, the tougher the steel (7). Recognizing this relationship, it was concluded that grain size requirements could be used to provide some assurance of reasonable fracture toughness in the absence of a CVN requirement. Hence, specifications emerged which attempted to insure fracture toughness via grain size control. These usually contained a statement similar to the following:

"The material shall be silicon killed, made by fine grain practice."

This process, explained later, requires the introduction of special chemicals during the steel melting process. These chemicals give the steel a potential for fine grain structure if the proper rolling procedure is followed.

As originally proposed, this research project is a two-part effort:

Part I: Determination of the effect of "fine grain" melting practice on the toughness of finished plate.

Part II: Determination of the effect of loading rate on the toughness properties of bridge steels.

This interim report is concerned with Part I of the project only. a separate report on Part II will be forthcoming.

Originally proposed under Part I of this project was a work plan involving reheat-treatment and subsequent physical testing to determine, primarily, the effect of various heat treatments on the grain size and related toughness properties of two popular bridge steels, A36 and A441.

As the Part I investigation progressed and the investigators digested more information concerning the measurement of grain size and its significance, it became apparent that serious inadequacies existed in the currently used McQuaid-Ehn method (ASTM E112) of grain size determination. It was found that the McQuaid-Ehn test, in itself, provided information which often was not indicative of the properties (fracture toughness) of the finished plate. Also, at about the same time this observation was made, the AASHTO Charpy V Notch energy requirements were established for all bridge steels. This more desirable "performance-type" specification virtually eliminated the need for grain size testing, at least for the purpose of fracture toughness control. The only remaining justification for retention of the "fine grain practice" requirement would be the added assurance of uniform mechanical properties (and toughness) across any given plate and from plate to plate within any given heat of steel.

Considering those arguments, which tended to discredit the value and necessity of grain size measurements by the McQuaid-Ehn method, it was decided that the testing originally proposed under Part I should be eliminated, but that this interim report should be written to document our findings supporting the above-mentioned contentions.

CONCLUSIONS

Our conclusions are as follows:

1. The McQuaid-Ehn test, currently used to indicate prior austenitic grain size, is by itself not a guaranteed indication of fracture toughness of hot rolled steel plate.

2. The McQuaid-Ehn test, currently used to indicate prior austenitic grain size, is valuable in determining whether "fine grain practice" (aluminum deoxidation) was observed in the steel melting process.

3. When it is associated with uniform carbide dispersion, <u>ferrite</u> grain size measured in the as-rolled plate is a more realistic indicator of fracture toughness than the prior <u>austenitic</u> grain size obtained in the McQuaid-Ehn test.

Metallurgical references also indicate that:

1. Grain refinement can be accomplished in the following ways:

   a) rolling (finishing) at a temperature below the grain coarsening temperature (Figure 2) in "killed, fine grain" steel.

   b) normalizing of "killed, fine grain" hot-rolled steel.

   c) quenching and tempering.

2. Decrease in susceptibility to brittle fracture can be associated with:

   a) fine ferritic grain structure.

   b) high ferrite-to-pearlite ratio in hot rolled steels.

   c) decreased carbon and phosphorus contents.

   e) the addition in amounts of 0.02 to 0.06% aluminum or aluminum and zirconium, titanium, vanadium, and/or niobium.

RECOMMENDATIONS AND IMPLEMENTATION

Midway through this investigation Caltrans adopted the AASHTO Group 2 Charpy testing requirements for most bridge steels. This implemented the larger original objectives to this work, i.e., the establishment of a workable toughness requirement for bridge steels, and rendered further investigation unnecessary.

DISCUSSION

General

In attempting to explain the influence of grain size on steel toughness, it should be noted that hot rolled steel properties are controlled primarily by the relative amounts and distributions of iron carbide (cementite) and iron (ferrite) (1) and by the strength of the ferrite in the finished steel plate. Hence, the mechanical properties of most plain carbon steels are dependent primarily upon the ferrite - cementite grain configuration rather than chemical element content (2). Along with the ferrite grains, in slow to moderately cooled steel, are interspersed grains of pearlite which is composed of ferrite and cementite in a lamellar arrangement. In addition to a small ferritic grain size (#7+), it is necessary that the ferrite-to-pearlite ratio be at least as large as 1 1/2 to 1 if good fracture toughness is to be realized.

Ferrite is the allotrope of iron that is commonly observed in bridge steels at room temperatures (an allotrope is an alternate form of an element, for instance, graphite and diamond are allotropes of carbon). Ferrite exists in steel as homogeneous crystals of "ferrite" and as a heterogeneous mixture with iron carbide in crystals of "pearlite". It is stable in bridge steels up to about 1600°F in its homogeneous form and about 1335°F in its heterogeneous or pearlite form. Above these temperatures it transforms to a second allotrope of iron called austenite which is unstable in bridge steels below 1335°F. The lower temperature is frequently referred to as the "lower critical transformation temperature". This temperature may vary as much as ± 50° in bridge steels depending on alloy content and heating or cooling rate.

Referring to Figure 1, it can be seen that on heating just above the lower critical transformation temperature (A_1), usually about 1335°F, all pearlite grains change to austenite. As the temperature is raised farther above A_1, the austenite dissolves more and more of the surrounding ferrite grains until at the upper critical transformation temperature (A_3) of about 1600 F, the last of the ferrite has been absorbed into the austenite, and austenitic grain structure prevails. These austenite grains grow in size in proportion to the temperature above A_3 to which they are heated. On slow cooling below A_1, the final product is a mixture of ferrite and pearlite/grains - the relative proportions of each being dependent on the carbon content and cooling rate, and tending to dictate toughness characteristics.

<u>"Killed, fine grain practice"</u>

Some specifications attempt to control fracture toughness by requiring that the steel be "killed" and made according to "fine grain practice".

The term "<u>killed</u>" simply implies that the steel has been deoxidized sufficiently for it to lie perfectly quiet when poured into the ingot mold. Or, in other words, there is no evolution of carbon monoxide gas during solidification. This is accomplished by the addition of silicon to the melt to convert oxygen in the steel to the stable oxide, SiO_2. This leaves no oxygen to react with the carbon and form carbon monoxide gas. The result is a sounder, more homogeneous steel with a slightly lower yield strength.

As was mentioned previously, 100% austenite is formed when the steel is heated above its upper critical (A_3) temperature. The austenite grains grow in size in proportion to the temperature above A_3 to which they are heated, i.e., the higher the steel is heated above its A_3 temperature, the larger the grains of austenite tend to grow. Since this austenitic grain growth cannot be reversed by cooling, it will normally result in a coarser final ferritic grain structure. Hence, it is often desirable to limit the extent of the growth by the addition of <u>aluminum</u> to the melt while it is in the ladle. This technique, constitutes what is popularly known as "<u>fine grain practice</u>", and steel made using this technique is often labeled "inherent fine grain" steel.

The effect of aluminum and of small additions of zirconium, titanium, vanadium and/or niobium in inhibiting austenitic grain growth at temperatures above A_3 is shown in Figure 2. These elements combine with nitrogen and carbon to form compounds that remain insoluble in the austenite grain boundaries below about 1900°F. The presence of these compounds in the grain boundaries in fine grained steels slows the enlargement or growth of austenite grains that normally occurs in coarse grain steels as the temperature increases above the lower (A_1) and upper (A_3) transformation temperatures (about 1350° and 1600°F respectively - at which temperatures pearlite and ferrite are transformed to austenite). Hence with these added compounds, the austenite grains in fine grain steel up to about 1900°F remain almost as small as when they were formed at 1600°F. When this fine grain steel is heated above about 1900°F, however, these inhibiting compounds are dissolved and the austenite grains enlarge and rapidly grow to be as big as they would be in coarse grained steels.

As previously explained, the enlargement of the austenite grains brought about by heating above 1900°F cannot be reversed by cooling back below 1900°F. The compounds that inhibit the enlargement of the austenite grains, however, are reprecipitated below this temperature. Thus, if the larger austenite grains are refined by normalizing or by rolling or forging below 1900°F, they remain smaller by virtue of the presence of the reprecipitated inhibitors than they were before normalizing, rolling or forging. The ferrite and pearlite grains that are subsequently formed from these smaller austenite grains when the steel is cooled back down through the transformation temperatures, are smaller then the grains that would have resulted from the transformation of larger austenite grains (such as those associated with coarse grained steel or with fine grained steel hot rolled above 1900°F).

In the McQuaid-Ehn test, to be described later, the 1700°F austenitic grain size is measured. From Figure 2, it can be seen that at 1700°F the "fine" and "coarse" grain steels differ drastically. This suggest that the McQuaid-Ehn test could be of value in determining whether or not "fine grain practice" had been observed in the melting operation. But, this information is not sufficient to reveal the true grain structure in the as-rolled (finished) plate. Referring to Figure 2, it is evident that even if "fine grain practice" is observed in the steel melting process, the finished plate could still exhibit a coarse grain structure if it had been rolled at a temperature above the grain-coarsening range, as is often the case.

One undesirable result of "fine grain practice", however, is poorer surface quality on the finished plate. It should be pointed out that a "fine grain practice" steel making process can only be effective if performed on "killed" steel.

It is obvious that specifications which attempt to control fracture toughness through a "fine grain practice" melting requirement are inadequate unless one or more of the following supplemental safeguards is specified by the steel user:

1) performing precracked Charpy impact test.
2) minimizing final rolling temperature.
3) post-roll normalizing treatments at minimum normalizing temperature.

The McQuaid-Ehn Test

The grain size currently referred to in steel specifications is the "prior austenitic grain size" commensurate with the "baking" temperature (1700 F) of the McQuaid-Ehn test method. "Prior austenitic grain size" refers to the maximum size that the austenitic grains were able to attain during the heating operation. The McQuaid-Ehn test method requires that the specimen be heated above its A_3 temperature to 1700°F, in a carbonaceous atmosphere, so that after cooling and the attendant return to ferrite grain structure, the prior (i.e., 1700°F) austenitic grain boundaries are retained in the form of rejected iron carbide and can be highlighted using a suitable etching agent. This method of revealing prior austenitic grain boundaries depends on controlled cooling such that the austenite is made to transform to pearlite with attending rejection of excess iron carbide to the austenitic grain boundaries (3). But the introduction of carbon and oxygen in the McQuaid-Ehn test alters the chemistry and makes the test specimen exhibit different grain structure than if the plate were heated to 1700°F in a noncarbonaceous atmosphere. Probably the greatest shortcoming of the McQuaid-Ehn method, however, lies in the fact that its 1700°F baking temperature does not necessarily simulate the production heat treatment (rolling temperature of the steel being tested. It should be pointed out that the prior austenitic grain size tending to influence the size of the cooled ferritic grains in a rolled steel plate is the austenitic grain size corresponding to the final rolling temperature or, in general, corresponding to the temperature of the most recent thermal conditioning that the plate has undergone, which may or may not have been 1700°F. For example, if a plate is finish-rolled at, say 2000°F, not 1700°F as implied by the use of the McQuaid-Ehn method. The McQuaid-Ehn test, then, fails to disclose the effective (as-rolled) grain structure of a steel plate, but does reveal the austenitic grain size for all steels at 1700°F, regardles of each steel's actual thermal history.

More useful grain size information might be obtained by subjecting the test sample to a thermal conditioning which duplicates the production temperature rather than merely heating all steels to the specified 1700°F, regardless of their rolling temperature or post-roll heat treatment.

As mentioned above, fracture toughness is primarily controlled by ferrite grain size and distribution. Therefore, even a measurement of the true prior austenitic grain size would not provide the most realistic indication of the steel's fracture toughness. However, prior austenitic grain size can usually be related to final ferritic grain size in the sense that ferrite grains will always be smaller than the observed grains of austenite. Prior austenitic grain size can also be related to the uniformity with which the pearlite grains are distributed throughout the ferrite matrix.

It is generally accepted that a more realistic estimate of fracture toughness and Nil Ductility Temperature (NDT) might be obtained from the measurement of ferritic grain size in the finished plate (7). This could be done by etching and direct metallographic examination without reheating the specimen. This would thereby provide practical information as to the quality of the as-rolled (finished) plate. Attempts to relate finished grain size to the attenuation exhibited by ultrasonic waves have also had some success (6).

In summary, the McQuaid-Ehn test exhibits three basic shortcomings:

(1) it does not necessarily duplicate the actual thermal history of the plate.

(2) it introduces elements (carbon and oxygen) which affect the grain size exhibited by the test specimen.

(3) it measures austenitic rather then ferritic grain size.

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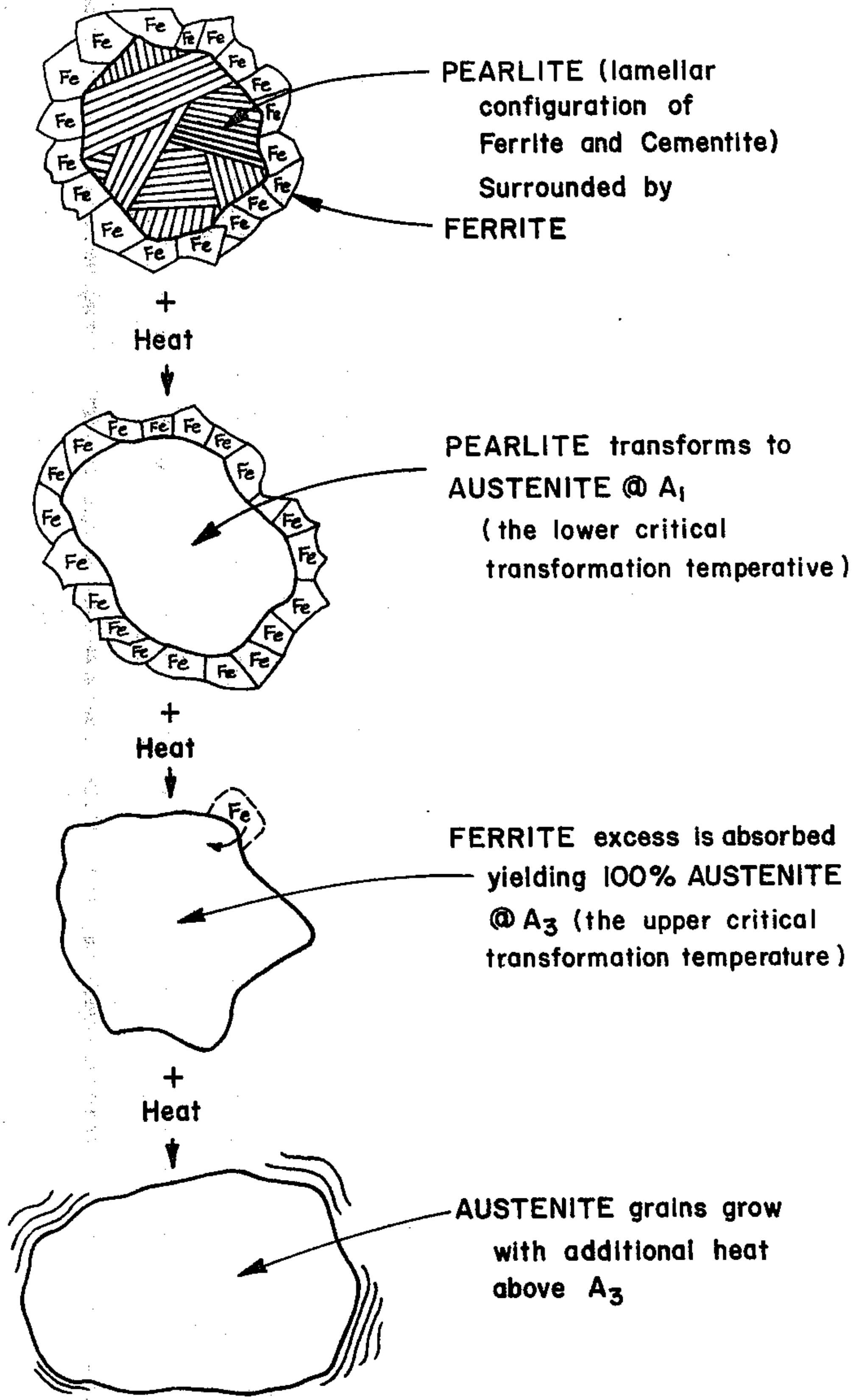

Figure 1. EFFECTS OF HEATING ON STEEL GRAIN STRUCTURE

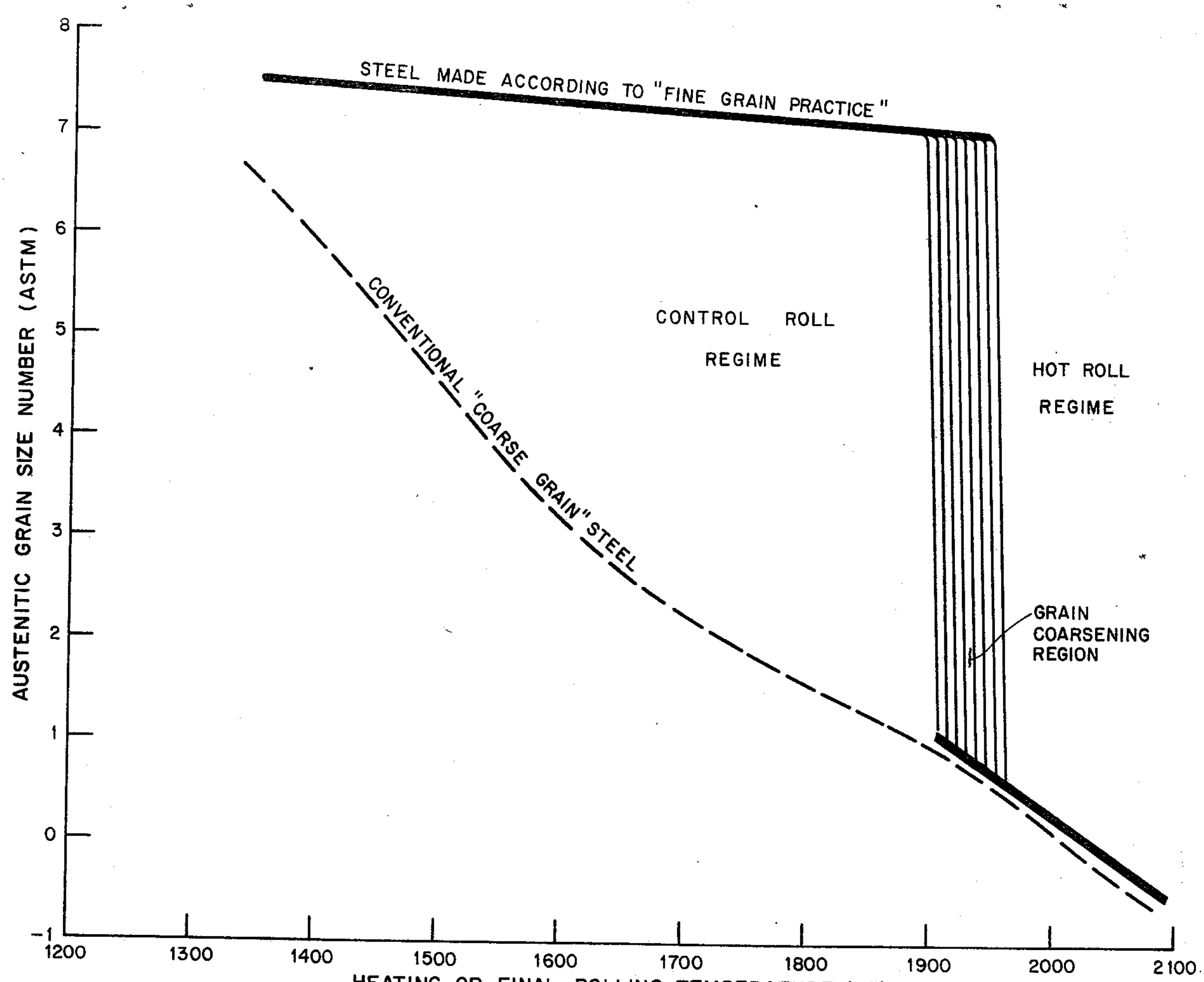

Figure 2. GRAIN SIZE AS FUNCTION OF TEMPERATURE